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Numerical Study on Temperature Distribution of Structural Components Exposed to Travelling Fire

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Abstract

In order to investigate the structure behavior under travelling fire, the numerical simulation of a full-scale travelling fire test with wooden fuels was completed by using FDS. The fire development and the heat release rate (HRR) were obtained. The temperature information, including gas temperature in the smoke layer, column surface temperatures at different heights, steel beam temperature and concrete ceiling temperature, were calculated from the FDS simulation. Although the compartment was rather small, obvious differences in temperature of the upper smoke layer and the steel beam, caused by the travelling fire, were observed. The maximum gas temperature under the ceiling was close to 1000 °C.

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Keywords: temperature distribution, travelling fire, structural component, FDS

1. Introduction

In view of recent large fires in tall buildings, structures have been observed to have easily lost stability or even collapse during fire. To understand such events, structural behavior under fire loading is more and more of a concern for researchers. Some numerical models have been developed to simulate the behavior of isolated structural components. A series of fire resistance tests [1-4] for structural components under different fire scenarios, such as ISO 834 standard fire, natural fire and travelling fire, have been carried out during the last decade. However, lack of validation with full-scale experimental data limit the use of numerical models in fire safety design of structures [5-6].

In traditional design fires, the uniform temperature conditions are always assumed throughout the whole compartment to analyze the structure behavior. However, it is very unlikely that a fire grows uniformly over an entire enclosure floor area [7]. Usually it starts at some distinct point and then moves in some manner across the enclosure. Some studies [8-9] show that in some cases travelling fire could better describe the temperature conditions for the structural components.

In this paper, the fire scenario of a full-scale travelling fire test was studied numerically by FDS [10]. The fire source was dependent on the detailed wooden fuel information. The fire development and heat release rate were obtained. The temperature variation of upper hot smoke layer was calculated, which was important for the behavior of beam, column and connection. The surface temperatures of the structural components, such as beam, column and slab, were also obtained.

2. FDS model for travelling fire

The FDS model, focused on the fire development and temperature distribution of the travelling fire test, has been completed. The dimension of the full-scale compartment was 12 m long, 9 m wide and 4 m high. The fire load was created by piles from wooden cribs (50×50×1000 mm). 8×3 wooden piles were placed closely together. Each pile consisted of 6 layers with 7 cribs, a total of 42 cribs. A linear ignition source was used on the left-hand side by the aid of thin-walled channel filled by mineral wool and penetrated by paraffin in the third layer of cribs.

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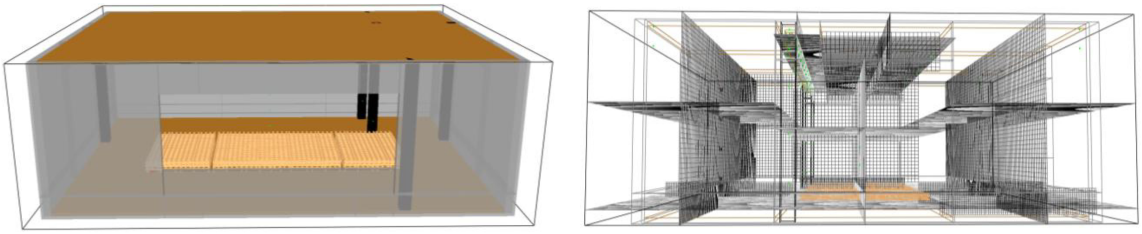
The dimension of the computational domain was 13 m by 10.8 m by 4.2 m, which was a little bigger than that of the compartment. The size of the opening located on the south wall was 2 m by 6 m. The grid size around the wooden fuels and the steel beam was 0.05 m by 0.05 m by 0.05 m, and the grid size in the remaining area was 0.1 m by 0.1 m by 0.1 m. In order to run the FDS job parallelly on the cluster, the computational domain was divided into 24 parts, as shown in Figure 1. The total grid number of the FDS model was 972810.



(a) outside view (b) grid design

Fig.1. FDS model for the travelling fire test.

There were four different materials in this model, including concrete, steel, mineral wool and softwood. The detailed properties of these materials are shown in Table 1, which are part of input data of the FDS model.

Table 1. Properties of materials used in the FDS model

	Concrete	Steel	Mineral wool	Softwood
Emissivity	0.85	0.80	0.85	0.90
Density [kg/m^3]	2300	7850	40	400
Specific heat capacity [kJ/kgK]	1.05	0.60	0.84	1.3
Heat conductivity [W/mK]	1.4	45	0.04	0.2
Heat of combustion [kJ/kg]	/	/	/	18000

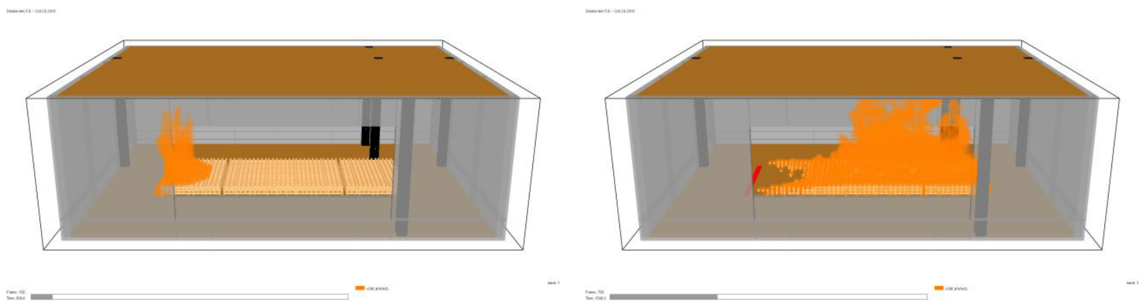
The following are the surface properties of the obstructions in the FDS model, which includes wood crib, concrete wall, floor & ceiling, steel beam and CFT column. The wood crib would disappear when they burn away in the Smokeview animation. The heat release rate per unit area (HRRPUA) and ignition temperature of softwood were obtained by the Cone calorimeter tests. The ignition time of softwood was approximated 30 s by using the RAMP_Q. The concrete wall was made up of two different materials with different thicknesses, inside concrete and outside mineral wool. The CFT column was also made up of two different materials, steel and concrete. Due to the limitation of FDS, the cross-section of the CFT column was square in the FDS model, which was a little different from the column in the real building.

A lot of temperature sensors were installed at different positions to obtain different temperature information, such as gas temperature in the upper layer, surface temperature of beam and ceiling, inside temperature of the CFT column, etc. The output quantities, such as TEMPERAUTR, WALL TEMPERATURE, WALL TEMPERATURE IN DEPTH, ADIABATIC SURFACE TEMPERATURE, were used in the FDS model.

3. Numerical results

3.1. Fire development

The wooden fuels were ignited along the left edge and travelled to right gradually. After 20 min, all the wooden fuels were ignited, and the fire reached the peak status around 25 min. The fire started to decrease rapidly after 30 min, and all the wood cribs nearly burnt away after 35 min. Figure 2 shows the fire development at two typical moments from the FDS simulation.



(a) 5 min (b) 25 min

Fig.2. Fire development at two typical moments from FDS simulation.

Figure 3 gives the heat release rate (HRR) of the fire scenario. The HRR increased to the peak at approximately 1300 s, and the peak HRR was nearly 20 MW. During the initial 1000 s, the HRR increased slowly to 10MW, while it increased rapidly to 20 MW within the following 300 s. All the wooden fuels were ignited and flashover occurred. The peak value of burning rate was approximately 1.05 kg/s. The variation trend was nearly the same as that of HRR during the whole fire development.

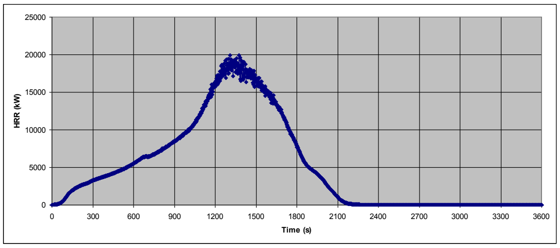


Fig.3. HRR of the travelling fire from FDS simulation.

3.2. Gas temperature in the upper layer

The gas temperatures in the upper smoke layer, at the height of 3.5 m, were obtained in the FDS simulation by using the output quantity 'TEMPERATURE'. The positions of the temperature sensors are close to the CFT columns, the steel beam, four corners and the center, as shown in Figure 4 (green points). There were four sensors around Column 1 at four sides. In the center of the compartment, there were five sensors at different heights. In the following, some of the gas temperature results will be shown.

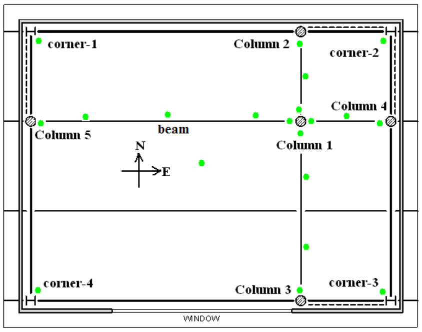
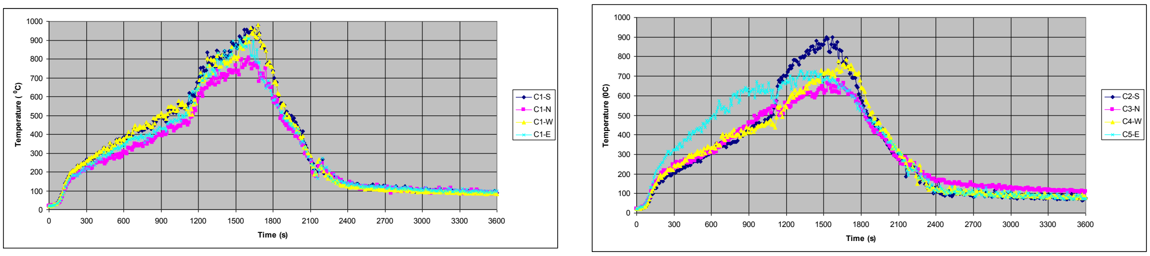


Fig.4. Thermocouple positions for the gas temperature in the FDS model.

Figure 5(a) shows the gas temperature results around Column 1 at four different sides. Although Column 1 was located beside the wooden fuels, there were no obvious differences among these four curves. The only deviation was that the temperature at the north side was slightly lower than the other three temperatures, since it was back to the wooden fuels. The maximum temperature around Column 1, approximately 950 °C, appeared at about 1600 s, which was 300 s later than that of the HRR due to the energy accumulation in the compartment.

The four columns, Column 2, 3, 4 and 5, were located beside the walls. Figure 5(b) shows the gas temperatures in the upper smoke layer around these four columns. The gas temperature around Column 5 increased more rapidly than the others during the fire growth period, since the fire travelled from west to east. However, the maximum temperature, approximately 900 °C, was the gas temperature around Column 2 at approximately 1500 s. Column 2 was located beside the north wall without any opening. All the generated smoke spread out though the opening on the south wall. Therefore the gas temperature around Column 2 was higher than the others during the full developed period. The gas temperature around Column 3 was the lowest as it was close to the opening.

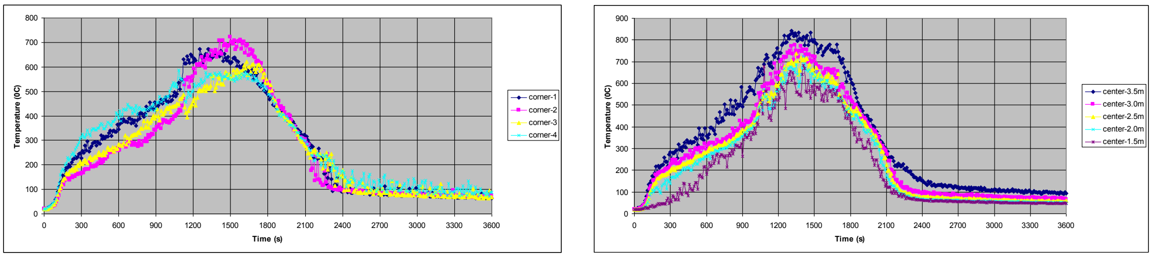


(a) (b) close to four CFT columns located beside the walls

Fig.5. Gas temperature in the upper layer from FDS simulation.

The gas temperatures in the upper smoke layer in the four corners were obtained, as shown in Figure 6(a). The maximum gas temperatures in the corner positions ranged from 600 °C to 700 °C, which were obvious lower than those around the CFT columns. As shown in Figure 7, corner-1 and corner-2 were close to the north wall without opening. Therefore the gas temperatures were approximately 100 °C higher than the other two temperatures. During the decay period, these four temperatures were almost the same.

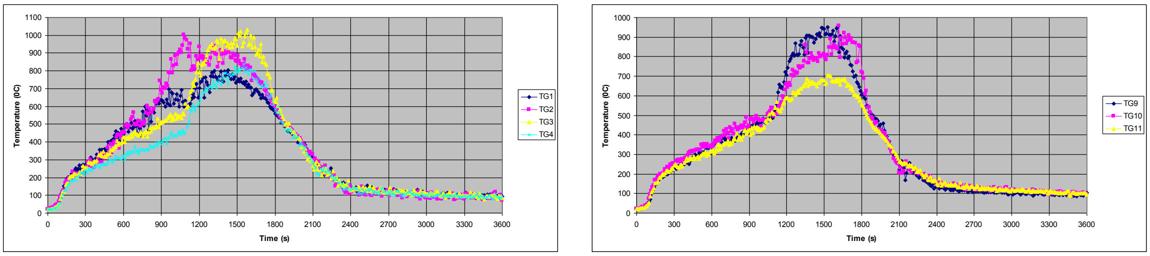
In the center of the compartment, five thermocouples were installed at different heights in the FDS model. Figure 6(b) shows the gas temperatures in the center of the compartment at five different heights, e.g. 1.5 m, 2.0 m, 2.5 m, 3.0 m and 3.5 m. The numerical results show that the temperature at the height of 3.5 m was higher than the others, and the maximum temperature was approximately 800 °C. The gas temperatures at the height of 3.0 m, 2.5 m and 2.0 m were almost the same, as they were all in the smoke layer. During the full-developed period, the gas temperature at the height of 1.5 m was also close to the others. It showed that the smoke layer was very thick, and therefore one-zone model should be more suitable for this fire scenario than two-zone model.



(a) (b)

Fig.6. Gas temperature in the upper layer from FDS simulation.

Figure 7(a) shows the calculated temperature results of TG 1-4 along the steel beam from west to east. As the fire spread from west to east, the temperatures of TG 1 and 2 increased more rapidly than the temperatures of TG 3 and 4 during the fire growth period. The positions of these thermocouples were very close to the wooden fuels, and then the temperatures were greatly affected by the fire source radiation. The maximum temperatures of TG 2 and 3 reached 1000 °C, while the maximum temperatures of TG 1 and 4 only reached approximately 800 °C. The temperatures started to decrease after 25 min, and there were no difference among these four positions after 30 min. Figure 7(b) shows the temperatures of the other three positions along the steel beam from north to south, with the name of TG 9, TG 10 and TG11. It is seen that the effect of distance from the opening plays an important role in the fire development. The temperature of TG 9 was the highest, since it was close to the north wall with higher heat feedback. The maximum temperature of TG 11 was only approximately 700 °C, as it was close to the opening with natural ventilation.

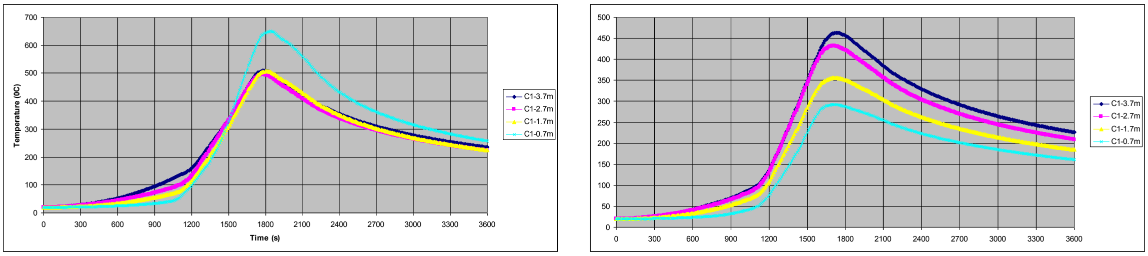


(a) (b)

Fig.7. Gas temperature in the upper layer from FDS simulation.

3.3. Temperature of CFT column 1

CFT Column 1 was located beside the wooden fuels in the compartment. In the FDS simulation, the surface temperatures of Column 1 at different heights and different sides were investigated. Figure 8 show the south and north surface temperatures at four different heights, i.e. 0.7 m, 1.7 m, 2.7 m and 3.7 m. During the initial fire growth period, the height of flame was not very high, and the generated smoke rose to the ceiling and spread below the ceiling. Therefore the column surface temperature increased with the height increasing before 20 min as shown in Figure 16 and 17. However, during the full developed period, the temperature distributions at the south and north surfaces were complete different. At the south surface, facing to the wooden fuels, the temperature at the height of 0.7 m was the highest, which reached approximately 650 °C after 30 min. The temperatures at other three higher positions were almost the same, the maximum values of which reached only 500 °C. The radiation from the flames played an important role for the temperature distribution at south surface. At the north surface, back on to the wooden fuels, the temperatures increased with the height increasing, and the highest temperature was only 460 °C.



(a) south surface (b) north surface

Fig.8. South and north surface temperatures at different heights of CFT column 1 from FDS simulation.

In the FDS model, the output quantity 'INSIDE WALL TEMPERATURE' was used to obtain the temperature distribution inside the column. Figure 9 shows the temperatures at six different depths, including 0 cm, 3 cm, 6 cm, 9 cm, 12 cm and 15 cm. It is shown that only the first two temperatures close to the surface increased obviously during the fire development and the others kept as the initial status due to the low heat conductivity of concrete.

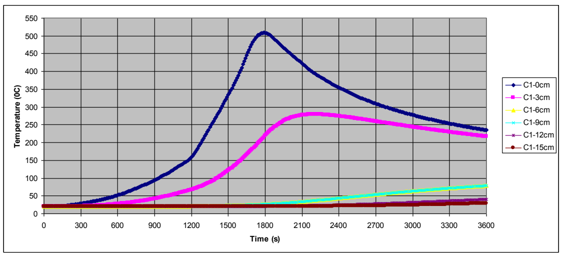
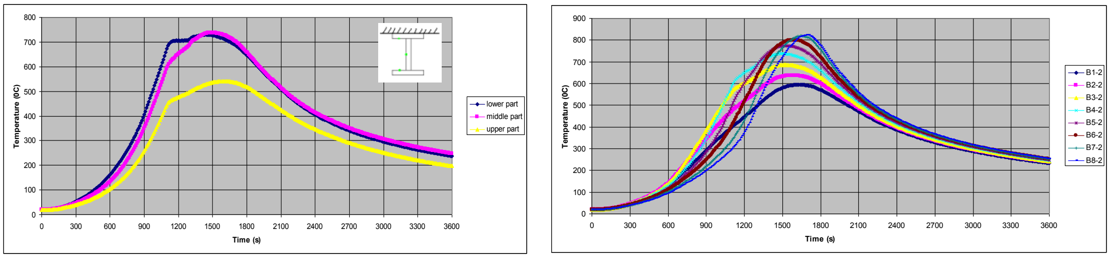


Fig.9. Inside temperature of CFT Column 1 at different depths from FDS simulation (3.7 m high position).

3.4. Temperature of steel beam

One steel beam with the length of 9.0 m was fixed under the ceiling between Column 1 and Column 5. The beam was made up of three parts with the shape as shown in Figure 10(a). The surface temperatures of the middle and lower parts were almost the same, while the surface temperature of the upper part was much lower. The reason is that the temperature of the concrete ceiling was obviously lower than the nearby smoke temperature. The maximum temperatures of the three parts were approximately 720 °C, 720 °C and 540 °C, respectively.



(a) different vertical positions (b) different horizontal positions

Fig.10. Surface temperatures of steel beam from FDS simulation.

During the test, the fire spread from west to east, naming travelling fire. To investigate the effect of travelling characteristic, eight thermocouples were installed in the middle part of the beam uniformly. Figure 10(b) shows the temperature distribution of the steel beam from west to east. It is clearly observed that the temperature distribution could be divided into two parts: B1-4 and B5-8. Although the heat conductively of steel is very high, the temperature distribution along the length direction was not uniform due to the fire source movement. The temperature was affected the radiation of the flame, and there were different increasing rate from west to east. During the full developed period, the maximum temperatures increased from west to east gradually.

3.5. Temperature of concreter ceiling

The ceiling in the FDS model was assumed as a flat concrete ceiling with the thickness of 20 cm. Figure 11 shows the inside surface temperature of the concrete ceiling at five different positions. The maximum surface temperature in the center position reached 620 °C, which was much higher than the temperatures in the four corners. Comparing with the smoke layer temperature below the ceiling, as shown in Figure 10 and 11, the temperature of concrete ceiling was approximately 250 °C lower, since the boundary condition of the outside surface is the ambient temperature.

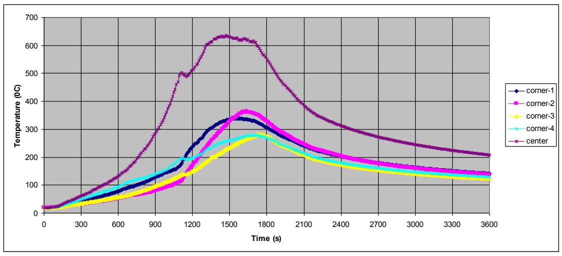


Fig.11. Surface temperature of concrete ceiling from FDS simulation.

4. Summary and conclusions

In the travelling fire test, 8×3 wooden piles with the height of 0.4 m were placed closely together in the center part of the compartment. The wooden piles were ignited in the western edge and the fire travelled from west to east. Some conclusions could be obtained according to the numerical simulation results:

1. The travelling fire lasted about 35 min and the maximum HRR was close 20 MW at the moment of 22 min.
2. As the fire travelled in the compartment and only one window opening was designed in the wall, the gas temperature distribution under the ceiling was not uniform. When the fire travelled to the eastern edge, the western part of wooden piles had already burn away. Therefore the maximum gas temperature was in the area around Column 1, which reached to about 1000 °C, but not in the center area.
3. The south surface temperatures of Column 1 at high positions were almost the same, but the surface temperature at low position was even higher. This phenomenon was caused by the flame radiation, as the wooden piles were placed close to the south side surface of Column 1. Differently, the surface temperature distribution at the north side of Column was much regular, which increased with the height increasing.

4. The inside surface temperature distribution of the concrete ceiling was not uniform. The maximum value of the ceiling temperature in the center position was about 600 °C, while the maximum values in the four corners were only about 300 °C.

5. As the fire travelled from west to east, the temperature distribution of the long steel beam along this direction was not uniform. During the full developed stage, the temperature of the upper part was about 200 °C lower than the temperatures of the middle and lower parts because of the different boundary conditions.

In the FDS simulation, the charring phenomenon of wood was not considered, and all the wooden cribs were completely burn, which may cause some differences from the real fire test. The numerical results will be compared with the experimental results in the further study.

Acknowledgements

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